Low energy analysis in CUORE-0

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Abstract.
    The majority of the mass of the Universe appears to be made of an unknown form of matter, called Dark Matter. The upcoming CUORE experiment, thanks to its large mass and low background, will be able to search for a DM annual modulation signal. The final sensitivity will depend on the achievable energy threshold.
    Here we present the low energy trigger developed for CUORE, some examples obtained with its application to CUORE-0 (the CUORE test detector) and the tools for the low energy analysis.

1. Introduction

The Standard Model of particle physics is able to describe only about 15 % of the matter content of the Universe [1]. The remaining part seems to consist of an unknown form of non-baryonic, non-relativistic and non-luminous matter, called Dark Matter (DM) [1, 2]. Direct DM detection of WIMPs (Weakly Interacting Massive Particles) is based on the observation of the recoil of a target nucleus after scattering elastically off a DM particle.

A powerful tool that can be exploited in the DM search is the annual modulation (AM) signature: the motion of the Earth around the Sun induces a modulation in the flux of DM through the detector, which consequently experiences an annual modulation in the interaction rate.

More generally, given the very low expected interaction rate, a detector should fulfill some requirements to have chances to see an interaction signal:

- low energy threshold (tens of keV at most),
- very low radioactive background near threshold (nuclear recoil discrimination desirable),
- high exposure ($\gtrsim 10\,\mathrm{kg \cdot y}$),
- good energy resolution ($\leq 10\,\mathrm{keV}$).

The CUORE experiment, designed to search for the neutrinoless double beta decay (0νDBD [3]) of ^{130}Te, which will consist of 19 towers of 52 TeO$_2$ crystals each, for a total mass of 741 kg, is going to take data starting from 2016 in the underground Laboratori Nazionali del Gran Sasso (LNGS), Italy [4, 5]. Its mass, together with the expected low background and good energy resolution ($\approx 1\,\mathrm{keV}$ for the best channels) make it an optimal candidate for DM direct search
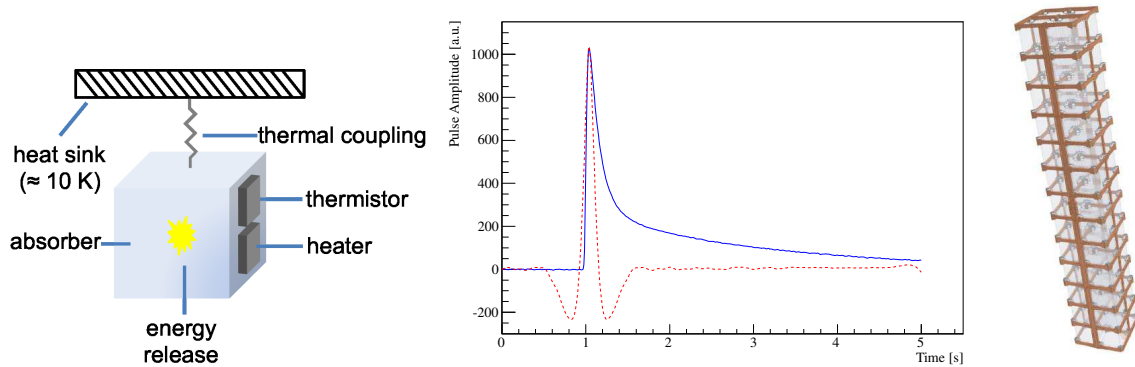
Figure 1. Left: CUORE bolometer schema with all the components indicated. Middle: pulse as produced by the detector (blue solid line) and filtered with the OF (red dotted line). Right: rendering of the CUORE-0 tower; the detector consists in 52 $5 \times 5 \times 5\,\mathrm{cm}^3$, $750\,\mathrm{g}$ TeO$_2$ crystals arranged in 13 floors, in groups of 4, for a total mass of $39\,\mathrm{kg}$.

using the AM approach. The final result will rely on the achievable low energy threshold and on the background in the low energy region.

A single tower prototype, CUORE-0 [6], has been operated in Hall A of the LNGS and now is no longer taking data. Given the mass of $39\,\mathrm{kg}$, CUORE-0 can be considered as an independent experiment with which to develop and test the low energy trigger and the tools needed for the low energy analysis that will be used in CUORE.

2. CUORE-0 and the bolometric technique

The CUORE and CUORE-0 experiments are based on the bolometric technique, which consists in cryogenic ($\approx 10\,\mathrm{mK}$) calorimetry. A bolometer is composed of two parts: an absorber and a sensor, as shown in Fig.1 left. The absorber is a crystal $-$ TeO$_2$ in this case $-$ in which an energy release, due to an interacting particle, raises the crystal temperature. The sensor, a neutron transmutation doped germanium thermistor (NTD$-$Ge) in CUORE and CUORE-0, measures this temperature variation. Subsequently, the accumulated heat is dissipated by means of a coupling to a thermal bath. The produced signal is a pulse (an example is in Fig.1 middle) the height of which depends on the released energy. Each crystal is equipped with a Joule heater, that produces reference signals needed for gain stabilization.

CUORE-0 consists in 52 TeO$_2$ $5 \times 5 \times 5\,\mathrm{cm}^3$ crystals of $750\,\mathrm{g}$ each, placed in groups of 4 over 13 floors, as shown in Fig.1 right. It is a CUORE tower prototype, built to validate the crystal production method, the cleaning procedure of the materials and the assembly line adopted to reduce the detector background, especially the main fraction in the 0νDBD region of interest, due to smeared α particles. The detector is hosted in the Hall A of the LNGS and took data from March 2013 to August 2013 and then from November 2013 to March 2015, collecting $9.8\,\mathrm{kg} \cdot \mathrm{y}$ of exposure.

The procedure adopted for the crystal growth allowed to reach bulk and surface contaminations to be less than $6.7 \cdot 10^{-7}\,\mathrm{Bq/kg}$ ($8.4 \cdot 10^{-7}\,\mathrm{Bq/kg}$) and $8.9 \cdot 10^{-9}\,\mathrm{Bq/cm}^2$ ($2.0 \cdot 10^{-9}\,\mathrm{Bq/cm}^2$) at 90% C.L., respectively, for ^{238}U (^{232}Th) decay chain [7]. Concerning the material facing the detector, contaminations have upper limits of $1.3 \cdot 10^{-7}\,\mathrm{Bq/cm}^2$ at 90% C.L. in both ^{238}U and ^{232}Th [8]. For a deeper explanation of the detector and of the 0νDBD results look at [9] and [10] and references therein.
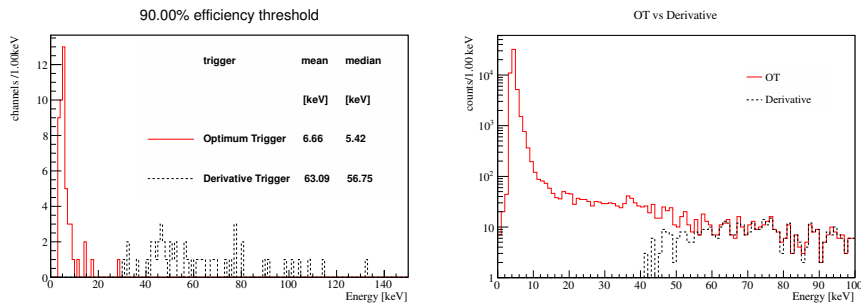
Figure 2. Comparison between the standard CUORE-0 trigger (Derivative Trigger, black dashed) and the Optimum Trigger (red solid) performances in a single dataset, as example. Left 90% trigger efficiency threshold, one entry per channel. Right: energy spectrum comparison below 100 keV for a single channel.

3. Low energy trigger

Given the low event rate, on the order of tens of mHz, it is possible both to store on disk the whole data flow from the detector and to use a trigger which is software generated. In particular, a dedicated software trigger has been developed to reach the low energy threshold needed for the DM search, which has been applied (in this case offline on a small sample of data saved on disk) to produce the results here presented. Its name is Optimum Trigger (OT) and is based on the matched filter technique, that allow to remove non-physical pulses [11]. The data buffer is divided into slices, filtered in the frequency domain and then triggered in the time domain. The filter is named Optimum Filter (OF) and its transfer function, which maximizes the signal to noise ratio, is

$$H(\omega) = \frac{S^*(\omega)}{N(\omega)} e^{-i\omega t_m}$$

where $S^*(\omega)$ is the Discrete Fourier Transform of the detector response, that we estimate averaging a large number of signal events, $N(\omega)$ the noise power spectrum (obtained from data) and t_m is a parameter to adjust the delay introduced by the filter and corresponding to the time of the maximum of the pulse. An example of a filtered pulse is given in Fig.1 middle.

Since the filtered pulses are less noisy, it is possible to push the threshold down to the keV region. In Fig.2 a comparison between the standard trigger, called Derivative Trigger (DT), and the OT is given. Fig.2 left presents an example of the distribution of the thresholds of each single channel with the two triggers, where the threshold is defined as the energy at which the trigger reaches the 90% of efficiency. Fig.2 right shows, as an example, the comparison between the low energy spectrum obtained for a single channel in a single dataset using the DT and the OT; no quality cuts are applied to the data to obtain this figure.

A slightly different version of the OT with an improved efficiency, with respect to the one presented in [11], is now used; a detailed description of this can be found in [12].

4. Analysis tools

In order to study the trigger efficiency as a function of energy for each channel and determine the energy threshold, it is possible to exploit the heater: producing a known number of pulses at different energies, one can count how many of them are seen by the trigger. In addition to the direct measurement, it is possible to describe the efficiency trend using *a priori* informations, as the filtered baseline resolution (σ) and the OT threshold (OT_{thr}, the minimum energy for
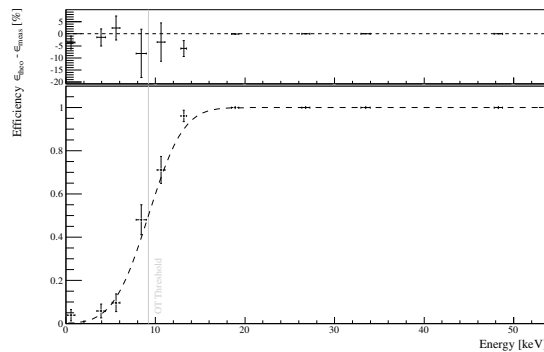
Figure 3. An example of OT trigger efficiency as a function of energy. In the lower panel, points represent the measured efficiency obtained by the ratio $\frac{triggered\,heater\,pulses}{fired\,heater\,pulses}$ (acquired in special runs with the heater firing at different energies), the dashed line is the expected efficiency trend by the *erf* and the vertical gray line is the OT threshold (50% efficiency for definition). Upper panel shows residuals.

a signal to be triggered), set to 3σ in CUORE-0. In fact it is expected to follow a Gaussian cumulative distribution function, that can be expressed using the error function (*erf*):

$$Eff(x) = \frac{1}{2}erf\left(\frac{x - OT_{thr}}{\sqrt{2}\sigma}\right) + \frac{1}{2}$$

where $Eff(x)$ is the efficiency at energy x. In Fig.3 the result of one of the heater scan measurements (called n-pulses runs) with superimposed the dashed line obtained with the *erf* is presented. In the upper panel residuals are reported. It is important to underline that the energy spectrum threshold is not necessarily equal to the OT_{thr}, but it can be different and, for example, set equal to the value at which the 90% efficiency is reached (as shown in the previous section and in Fig.2 left), while it is evident from the previous equation that at OT_{thr} efficiency is always equal to 50%.

From the data quality point of view, a single event selection is performed by mean of a shape indicator (SI):

$$SI = \sum_{i=0}^{L-1} \frac{\left(y_i^f - f_i\right)^2}{\sigma_L^2\,(L-2)}$$

where y^f is the filtered signal, f is the ideal filtered one and σ_L is the amount of noise expected in a window of length L (set equal to 4 ideal filtered signal widths). Applying a cut on the maximum value for this parameter it is possible to remove non-physical pulses like spikes, tower vibration and baseline jumps. An example is given in Fig.4 left, where, in blue, are highlighted the good events.

Additional selections are carried out to check detector properties during time: on a single run basis (a run lasts about 24 h) and on datasets basis. The cut on single runs consists in the selection of those ones with a baseline resolution lower than a certain value, currently median + 2 RMS of the run baseline resolution distribution. This is to consider only low noise operating condition. The study performed on datasets is to verify the calibration stability at low energy. This is done by means of a low energy peak produced by the heater glued to the crystal. If the position of a peak is incompatible with respect to the others, that dataset is discarded
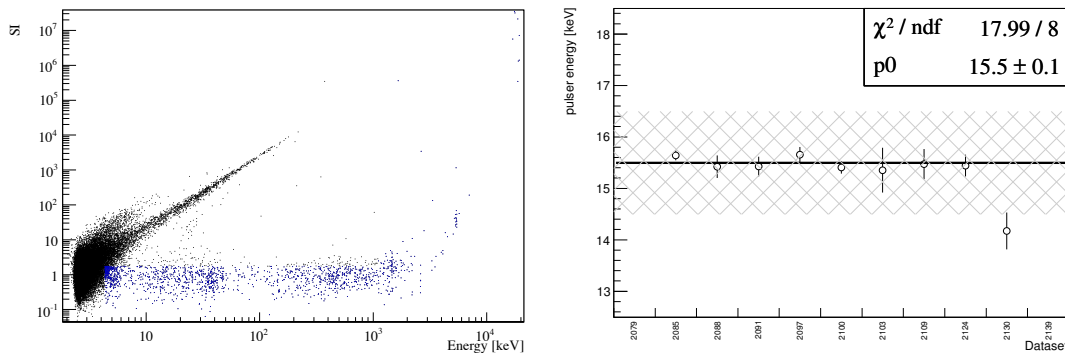
Figure 4. Data selection procedures. Left: distribution of the Shape Indicator parameter used to select good quality events (in blue) as a function of energy. Right: dataset selection based on the pulser position in the energy spectrum: if the peak position is compatible within $1\,\mathrm{keV}$ with the mean, the corresponding dataset is kept (in this case dataset 2130 is considered good, while the first and the last ones are absent since their calibrations are known to be of low quality for this channel).

from the analysis. The chosen limit is $1\sigma + 1\,\mathrm{keV}$ from the mean (see Fig.4 right), where $1\,\mathrm{keV}$ comes from the typical energy resolution of good CUORE-0 channels.

5. Conclusions

CUORE will start taking data in 2016 and thanks to its large mass ($741\,\mathrm{kg}$), long data-taking scheduled period ($5\,\mathrm{y}$) in controlled conditions, energy resolution ($\sim\,\mathrm{keV}$) and low foreseen background it will be able to search for DM interactions, looking for an annual modulated signal. Its final result will rely on the achieved energy threshold. To this end a dedicated trigger and analysis tools have been developed to push the threshold well below $20\,\mathrm{keV}$.

Here we have presented these tools applied to a bunch of data from a single CUORE tower prototype, namely CUORE-0.

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